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# Influence of income difference on carbon and material footprints for critical metals: the case of Japanese households

Yosuke Shigetomi[1,2,3*], Keisuke Nansai[2], Shigemi Kagawa[4] and Susumu Tohno[1]

*Correspondence: shigetomi.yosuke@nies.go.jp
[1] Graduate School of Energy Science, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto, Kyoto 606-8501, Japan
Full list of author information is available at the end of the article

**Abstract**

This study simultaneously analyzed the carbon and material footprints for three critical metals (neodymium, cobalt, and platinum) in Japanese households with different income levels. These metals are critical for new energy technologies, such as electric vehicles and rechargeable batteries, and are thus central to carbon footprint reductions. The policy implications of the trade-offs between GHG mitigation and critical metal consumption are considered within the context of differences in income. A global link input–output model representing national and international supply chains was employed to quantify the footprints according to household income quintile. In addition, the square root scaling method was used to compare footprints among households, considering differences in household size and their footprint characteristics. It is found that the degree of similarity among the carbon and material footprints for the three target metals was not very high [Spearman's rank correlation coefficients between them were 0.34 (neodymium), 0.63 (cobalt), and 0.10 (platinum)], implying that differences in relative household demand should be carefully considered based on differences in target footprints. The results of this study were compared to a similar study conducted in the UK to identify similarities and differences among footprints. In both countries, the carbon footprint intensity of household expenditure decreases as household income increases. The findings of this study also revealed that, in contrast to the case of carbon footprints, the material footprint intensities of household expenditure rise as household income increases, particularly in the case of neodymium. Consequently, the implementation of subsidies aimed at reducing carbon footprints and stimulating the economy should carefully consider the concomitant increase in material footprints. Importantly, such considerations are not only applicable to developed countries, but also emerging countries, the living standards of which are expected to increase markedly in the near future.

## 1 Background

Human society consumes a great deal of energy and resources in order to sustain economic activities and promote economic development. In response to the sustained increase in anthropogenic loads on the global environment, environmental footprint analysis has been used to quantify pressures induced by economic activity (Hoekstra and Wiedmann 2014). Footprint analysis is used to identify entire product life cycles and the loads associated with consumption. In recent years, the application of footprint analysis has expanded from using environmental indicators to using social indicators within the context of sustainability (Čuček et al. 2012; Alsamawi et al. 2014; Simas et al. 2014). Indeed, the application of a "Footprint Family" (see Galli et al. 2012, 2013; Fang et al. 2014) to develop sustainable and interdisciplinary policy measures that integrate more than one footprint indicator is increasing (Giljum et al. 2011; Ewing et al. 2012; Steen-Olsen et al. 2012). Fang et al. (2014) considered that a shift toward the integration of footprint indicators is likely, as no single indicator can be employed to analyze all anthropogenic loads. For example, Steen-Olsen et al. (2012) quantified carbon, land footprints, and (blue) water footprints in the European Union (EU)-27 nations, which correspond to greenhouse gas (GHG) emissions, land use, and water resources, respectively. They concluded that although these footprints are intrinsically different, they are also mutually influential, and that reductions in one suggest a hidden trade-off with the other.

The application of multi-criteria decision making in industrial policy is common practice. The European Commission (EC) started promoting the use of multiple footprints to analyze the footprints of products and organizations (EC 2013). Similarly, the 17 sustainable development goals put forward by the United Nations also need to consider multiple criteria and their synergies and trade-offs (Cucurachi and Suh 2015).

However, such multi-criteria assessments need to take into account consumer-side loads as well as producer-side loads. Numerous studies have quantified the direct and indirect environmental loads associated with household (i.e., consumer-side) consumption (e.g., Munksgaard and Pedersen 2000; Pachauri and Spreng 2002; Lenzen et al. 2004a; Druckman and Jackson 2009; Druckman et al. 2012; Chitnis et al. 2012; Wiedenhofer et al. 2013; Duarte et al. 2014). Household consumption has been demonstrated to be the greatest contributor to national carbon footprints (Hertwich and Peters 2009; Hertwich 2011). In order to analyze differences in the lifestyles of households, many studies have focused on socioeconomic and demographic factors, such as household income and age of the householder (Webber and Matthews 2008; Druckman and Jackson 2009; Kronenberg 2009; Girod and de Haan 2010; Jones and Kammen 2011; Saunders 2013; Chitnis et al. 2014; Shigetomi et al. 2014, 2015). However, except for studies that have specifically applied GHG emissions and energy consumption as multi-criteria, relatively few studies have addressed multiple household loads to date (Nansai et al. 2007; Hubacek et al. 2009; Kerkhof et al. 2009; Reynolds et al. 2015). For example, Reynolds et al. (2015) analyzed carbon, energy, water, and waste footprints associated with weekly food consumption in Australian households.

In order to obtain a more complete picture of environmental loads instigated by household consumption, the use of metal resources needs to be quantified in conjunction with GHG emissions, as some metals play a key role in new energy technologies, such as in electric cars and fuel cells. Among these metals are the so-called "critical metals," which are subject to supply constraints (National Research Council 2008; EC 2010). Neodymium is a rare earth metal that is primarily used to produce the permanent magnets in electric motors. Cobalt is commonly used to produce the positive electrodes in lithium-ion rechargeable batteries, and in the superalloys used in aerospace and other engineering applications. Platinum is used in the manufacture of catalytic converters in vehicle exhaust pipes and in applications in the electronics industry.

However, no studies have examined the similarities and differences between the carbon and material footprints for these critical metals (material footprints represent both direct and indirect material requirements of final demand). Indeed, although improvements in resource efficiency have been proposed in some states, such as the dematerialization policy described in The Roadmap to a Resource Efficient Europe (EC 2011), few studies have precisely examined the material footprints for minerals in individual nations (Giljum et al. 2015; Wiedmann et al. 2015).

Against this background, this study simultaneously analyzed the carbon and material footprints for the three critical metals (neodymium, cobalt, and platinum) in Japanese households with different income levels. In addition, the policy implications of the trade-offs between GHG mitigation and critical metal consumption are considered within the context of these differences in income.

## 2 Methods and data

### 2.1 Estimating carbon and material footprint intensities and household expenditures by income level

#### *2.1.1 Carbon and material footprints per unit expenditure for commodities consumed by households*

In recent years, the multiregional input–output (MRIO) models (Lenzen et al. 2004b; Wiedmann 2009; Moran and Wood 2014) that describe the input–output structure of international supply chains (Yamano and Ahmad 2006; Lenzen et al. 2012a; Tukker et al. 2013; Dietzenbacher et al. 2013; Wood et al. 2014) have also been used for environmental footprint calculations (e.g., Hertwich and Peters 2009; Feng et al. 2011; Lenzen et al. 2012b; Weinzettel et al. 2013; Wiedmann et al. 2015). The benefit of employing MRIOs for footprint analysis is that they clearly identify and represent the production technologies of individual nations, and that national system boundaries can be extended to include international supply chains (Weinzettel et al. 2014). In order to quantify carbon and material footprints for Japanese households, we clarified the expenditure on commodities by each household (million Japanese yen: M-JPY). The footprint per unit expenditure, or the footprint intensities, was calculated using a global link input–output model (GLIO) (Nansai et al. 2009, 2013a, b). The GLIO is a MRIO composed of a Japanese input–output structure with 409 sectors of domestic commodities and 409 sectors of imported commodities, and overseas sectors covering 230 countries and regions.

Derivation of the carbon and material footprint intensities is elaborated in Nansai et al. (2012) and Shigetomi et al. (2015), respectively. However, to introduce the structure of the GLIO, the method used to calculate material footprint intensities is described briefly below. Vector **q,** whose elements represent the material footprint intensities of commodities supplied to Japanese households, is calculated as shown in Eq. 1:

$$\mathbf{q} = \mathbf{d}(\mathbf{I} - \mathbf{A})^{-1} \tag{1}$$

Vector $\mathbf{q} = \left( \mathbf{q}^{JD} \; \mathbf{q}^{JI} \; \mathbf{q}^{G} \right)'$ consists of sub-vectors $\mathbf{q}^{JD} = \left(q_i^{JD}\right)$, $\mathbf{q}^{JI} = \left(q_i^{JI}\right)$, and $\mathbf{q}^{G} = \left(q_q^{G}\right)$, where elements $q_i^{JD}$ and $q_i^{JI}$ denote the material footprint intensities (t/M-JPY) of Japanese domestic commodity $i = (1 \ldots n^{JP};\, n^{JP} = 409)$ and of directly imported commodity $i$, respectively. As an aside, $q_q^G$ represents the material footprint intensities (t/M-JPY) of overseas commodities $q = (1...n^G; n^G = 230)$, but this is not used further in the present study. Row vector $\mathbf{d} = \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{i}^G \end{pmatrix}$ has the same dimensions as vector $\mathbf{q}$ and includes the summation vector $\mathbf{i}^G$ in which all elements are unity. Matrix $\mathbf{I}$ is an identity matrix.

Matrix $\mathbf{A}$ is a mixed-unit input coefficient matrix consisting of block matrices $\mathbf{A}_{11}$, $\tilde{\mathbf{A}}_{13}$, $\tilde{\mathbf{A}}_{31}^{(k)}$, $\tilde{\mathbf{A}}_{32}^{(k)}$, and $\tilde{\mathbf{A}}_{33}^{(k)}$, as is shown in Eq. 2:

$$\mathbf{A} = \begin{pmatrix} \mathbf{A}_{11} & \mathbf{0} & \tilde{\mathbf{A}}_{13} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \sum_{k=1}^{l} \tilde{\mathbf{A}}_{31}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{32}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{33}^{(k)} \end{pmatrix}, \tag{2}$$

where $\mathbf{A}_{11}$ is the input coefficient matrix based on monetary units describing the input structure of domestic commodities $i$ with regard to Japanese domestic commodities $j = \left(1 \ldots n^{JP}\right)$, and $\tilde{\mathbf{A}}_{13}$ is a matrix showing the import structure of domestic commodities $i$ in overseas sector $q$. $\tilde{\mathbf{A}}_{31}^{(k)}$ is a matrix showing the input structure of critical metals contained in traded goods $k$ in overseas sector $p = \left(1 \ldots n^G\right)$ for Japanese domestic commodities $j$, and $\tilde{\mathbf{A}}_{32}^{(k)}$ is a matrix showing the input structure of critical metals contained in traded goods $k$ of overseas sector $p$ for the input of commodities $j$ imported directly to Japanese final demand. $\tilde{\mathbf{A}}_{33}^{(k)}$ is a matrix showing the input structure for critical metals contained in traded goods $k$ of overseas sector $p$ for overseas sector $q$. The superscript—denotes a matrix whose coefficients are based on mass units. $k = (1 \ldots l)$ represents the type of traded goods that contain target metals, with $l = 153$ used for neodymium, $l = 160$ for cobalt, and $l = 151$ for platinum. These traded goods were selected from the Base pour l'Analyze du Commerce International (BACI) database, which is an improvement of the UN Comtrade database and defines traded goods based on the Harmonized Commodity (HS) code. See Nansai et al. (2015) for a detailed explanation of the mixed-unit input coefficient matrix $\mathbf{A}$ and Nansai et al. (2014) for the selected traded goods.

#### *2.1.2 Household expenditures by income level*

To estimate the consumption trends of different household income levels, this study used the method of Shigetomi et al. (2014). Briefly, the method provides domestic household consumption expenditure data for household attributes (e.g., household size) based on values in the Japan input–output table (JIOT) using household survey data (National Survey of Family Income and Expenditure: NSFIE). In addition to the study of Shigetomi et al. (2014), which estimated consumption expenditures for six householder age groups, we also obtained household expenditures for each income quintile using the values from the JIOT (2005) and NSFIE (2004), as follows. Household income quintiles were calculated by dividing all of the households into five groups (quintiles) according to income (i.e., 20 % of all households in each group). These income groups were then ordered from the lowest to the highest, i.e., Quintile1 to Quintile5, abbreviated as Q1, Q2, Q3, Q4, and Q5, respectively.

First, we obtained $r_{ib}$, which represents the expenditure ratio of commodity $i$ per unit expenditure by each household income quintile $(b = 1...5)$ for Q1 to Q5 using Eq. 3.

$$r_{ib} = \frac{P_{ib}}{\sum_{i=1}^{N} P_{ib}}. \tag{3}$$

Here $P_{ib}$ is expenditure per month (M-JPY/m) on commodity $i$ by each household income quintile. $N = 409$ is the number of commodity sectors.

In Eq. 4, $s_{ib}$ denotes the market share of commodity $i$ among households ($b = 1\ldots5$). $M = 5$ denotes the number of household attributes.

$$s_{ib} = \frac{P_{ib}}{\sum_{b=1}^{M} P_{ib}}. \tag{4}$$

A quadratic programming (QP) algorithm was used to determine the optimal solution for variables $\tilde{r}_{ib}$ and $\tilde{s}_{ib}$ with the objective function defined in Eq. 5 which minimizes the sum of the differences between $r_{ib}$ and $\tilde{r}_{ib}$ and between $s_{ib}$ and $\tilde{s}_{ib}$ under the constraints of Eqs. (6) through (9).

$$\underset{\tilde{r}_{ib},\tilde{s}_{ib}}{\text{Min.}} \sum_{b=1}^{M}\sum_{i=1}^{N}\left(\frac{\tilde{r}_{ib}-r_{ib}}{r_{ib}}\right)^2 + \sum_{b=1}^{M}\sum_{i=1}^{N}\left(\frac{\tilde{s}_{ib}-s_{ib}}{s_{ib}}\right)^2 \tag{5}$$

s.t.

$$g_i = \sum_{b=1}^{M} \tilde{r}_{ib} g_b \tag{6}$$

$$\sum_{i=1}^{N} \tilde{r}_{ib} = 1 \tag{7}$$

$$\tilde{r}_{ib} \geq 0 \tag{8}$$

$$\tilde{s}_{ib} = \tilde{r}_{ib} g_b / g_i. \tag{9}$$

Here $g_i$ and $g_b$ represent the total consumption expenditure of commodity $i$ based on the JIOT and the total consumption expenditure by household income quintile, respectively. Equation (6) shows that $g_i$ should be equal to the sum of consumption expenditure of commodity $i$ for each of the households. Since $\tilde{r}_{ib}$ is a ratio, and the total of each household is 1 (nonnegative), Eqs. (7) and (8) are satisfied. Equation (9) expresses the relationship between $\tilde{r}_{ib}$ and $\tilde{s}_{ib}$.

We determined $g_{ib}$(M-JPY/y), which is the consumption expenditure of commodity $i$ by household income quintile, by multiplying the optimal solutions of the above QP problem, $\hat{\tilde{r}}_{ib}$, and $g_b$. Since $g_{ib}$ is based on consumers' prices and the carbon footprint intensity (t-$CO_2$eq/M-JPY) and material footprint intensity (t/M-JPY) are calculated on a producers' price basis, $g_{ib}$ was converted to a producers' price basis, $f_{ib}$ (see Shigetomi et al. 2014).

By multiplying the ratio of imported commodities $im_i (0 \leq im_i \leq 1)$, obtained from the JIOT, by $f_{ib}$, the consumption expenditure for domestic commodities $f_{ib}^{JD}$ (M-JPY/y) and the consumption expenditure for imported commodities $f_{ib}^{JI}$ (M-JPY/y) were determined as follows:

$$f_{ib}^{JD} = (1 - im_i) f_{ib} \tag{10}$$

$$f_{ib}^{JI} = im_i f_{ib}. \tag{11}$$

Accordingly, the sum of consumption expenditure for each household income quintile estimated in this study is consistent with the total household expenditure in the JIOT.

#### *2.1.3 Adjustment of educational and medical expenditures used in the footprint calculations*

Expenditures related to education and health care are subsidized by the Japanese government. We incorporated the amount of these subsidies into the consumption expenditures obtained in the previous subsection and used these adjusted expenditures in subsequent calculations of the carbon and material footprints.

### 2.2 Calculation of equivalized consumption expenditure by household income quintile

Although it is anticipated that household expenditure increases with household size, this increase is not linear. Furthermore, even when household size is the same, the number of adults and children in a household can vary, making simple comparisons of household footprint characteristics per inhabitant difficult. In this study, the consumption expenditure per household was therefore equivalized using the "square root scale" (OECD 2008). This scaling method allows us to consider differences in the size of individual households and their associated carbon and material footprints. This is similar to the method employed in previous studies in which households were compared using a conventional "OECD-modified equivalence scale" (Girod and de Haan 2010; Chitnis et al. 2014). However, this method was not used because, according to an OECD working paper (OECD 2008), the reported differences between the results obtained using these two scaling methods are small.

We calculated the equivalized consumption expenditure of commodity $i$ for each household income quintile, $y_{ib}^{JD}$ and $y_{ib}^{JI}$, using Eqs. (12) and (13) with $f_{ib}^{JD}$ and $f_{ib}^{JI}$, respectively. These variables were used to calculate the carbon and material footprints for comparisons between households.

$$y_{ib}^{JD} = \frac{f_{ib}^{JD}}{H_b \sqrt{n_b}} \tag{12}$$

$$y_{ib}^{JI} = \frac{f_{ib}^{JI}}{H_b \sqrt{n_b}}, \tag{13}$$

where $H_b$ denotes the number of households in each household income quintile. In the case of this study, the number of households in each quintile is identical for all households ($H_b = 9.81 \times 10^7$), since the analysis distinguishes households by income quintile.

$n_b$ denotes the size of the household income quintile, with $n_1 = 1.49$, $n_2 = 2.11$, $n_3 = 2.64$, $n_4 = 3.11$, and $n_5 = 3.53$.

### 2.3 Calculation of carbon and material footprints induced by equivalized household consumption

Carbon footprints induced by equivalized household consumption were calculated in a similar manner to Shigetomi et al. (2014). The equivalized carbon footprint for each household income quintile was defined as the sum of direct emissions generated by combustion of fuel for private transport, heating appliances, etc., and indirect emissions associated with household consumption of commodities (see Shigetomi et al. (2014) for details of the method).

$MF_b$, which denotes the equivalized material footprint for each household income quintile, was calculated using Eq. (14).

$$MF_b = \sum_{i=1}^{N} q_i^{JD} y_{ib}^{JD} + \sum_{i=1}^{N} q_i^{JI} y_{ib}^{JI}, \tag{14}$$

where $q_i^{JD}$ and $q_i^{JI}$ denote the material footprint intensities (t/M-JPY) for domestic commodity $i$ and for imported commodity $i$, respectively. $y_{ib}^{JD}$ and $y_{ib}^{JI}$ express the equivalized consumption expenditure of commodity $i$ for each household income quintile as calculated in Sect. 2.2. This study used the material footprint intensities obtained for neodymium, cobalt, and platinum, elaborated in Sect. 2.1.

### 2.4 Aggregation of commodities based on category of individual consumption by purpose (COICOP)

In order to express the calculated equivalized consumption expenditure, carbon footprints, and material footprints for the three target metals examined in this study, we aggregated 409 commodity sectors into 17 categories based on the category of individual consumption by purpose (COICOP) data published by the United Nations Statistics Division (Table 1). COICOP is a classification for all areas of individual consumption expenditures and has been used in numerous previous studies (Collins et al. 2006; Tukker and Jansen 2006; Wiedmann et al. 2006). The categories 1–16 are in line with the previous studies by Druckman et al. (2011) and Chitnis et al. (2012, 2014) in order to allow for carbon footprint comparisons associated with direct household energy consumption. The 17th category contained the household consumption expenditure sectors listed in the JIOT (e.g., retail trades, wholesale trades, public administration) that did not belong to the other 16 categories.

### 2.5 Limitations of the methodology used to quantify carbon and material footprints

The GLIO model used in this study describes domestic commodity sectors with very high sectoral resolution. On the other hand, each of the overseas sectors was abbreviated into a single sector. Hence, the model represents the input–output structure for the target metal among foreign countries, but it does not describe the supply chain structure for the foreign commodities that contain each metal. The accuracy with respect to the

**Table 1 Correspondence between 17 commodity categories employed in this study and those of the Category of Individual Consumption by Purpose (COICOP) employed by the United Nations Statistics Division**

| Number | COICOP | Description |
|---|---|---|
| 1 | 1 | Food and non-alcoholic beverages |
| 2 | 2 | Alcoholic beverages, tobacco, and narcotics |
| 3 | 3 | Clothing and footwear |
| 4 | 5 | Furnishings, household equipment, and household maintenance |
| 5 | 6 | Health |
| 6 | 8 | Communication |
| 7 | 9 | Recreation and culture |
| 8 | 10 | Education |
| 9 | 11 | Restaurants and hotels |
| 10 | 12 | Miscellaneous goods and services |
| 11 | 4.5.1 | Electricity |
| 12 | 4.5.2 | Gas |
| 13 | 4.5.3 | Other fuels |
| 14 | 4.1–4.2 | Other housing[a] |
| 15 | 7.2.2.2 | Vehicle fuels and lubricants |
| 16 | Rest of 7 | Other transport[b] |
| 17 | | Other services[c] |

[a] House rent, house repair, water fees, waste disposal costs, etc.

[b] Transportation utilization fees for transport modes such as airplanes, buses, and taxis

[c] Some commodities, such as Wholesale and Public Administration not belonging to a Category of Individual Consumption by Purpose (COICOP) category shown above

indirect effect of both GHG emissions and metal consumption in countries other than Japan may therefore be lower.

The material data embodied in the GLIO are obtained by multiplying the trade volumes of each commodity by its percentage metal content as described in Nansai et al. (2014). Given the large number (231) of targeted countries, however, the metal content of some of the commodities exported from certain foreign countries was unavailable. In these cases, the relative metal content of the same Japanese export commodity was used instead. As a result, the metal flows associated with export commodities from developing countries may have been overestimated in some cases. This is because Japanese exports of high-tech commodities might be of higher quality (e.g., low energy consumption, low noise, high durability, multi-functional) and might require more critical metals than the same commodities produced in developing countries. Since these data were then linked to the GLIO model, the material footprints via exports from developing countries are also likely to have been overestimated.

## 3 Results

### 3.1 Equivalized consumption expenditure by household income quintile

Figure 1 presents the equivalized consumption expenditure (M-JPY/y) for 17 COICOP categories by household income quintile. The mean denotes the simple arithmetic average of each household; the same applies to Figs. 2, 3, 4, and 5. The total consumption expenditure increases uniformly as the household income increases and the difference between the minimum Q1 (2.53M-JPY) and the maximum Q5 (4.65M-JPY)

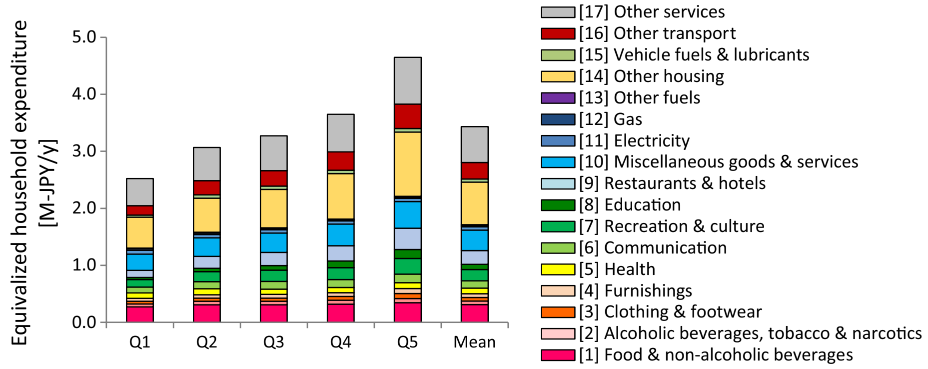

**Fig. 1** Equivalized household consumption expenditure (M-JPY/y) for each household income quintile in 2005. Means are simple arithmetic averages of five expenditures per household

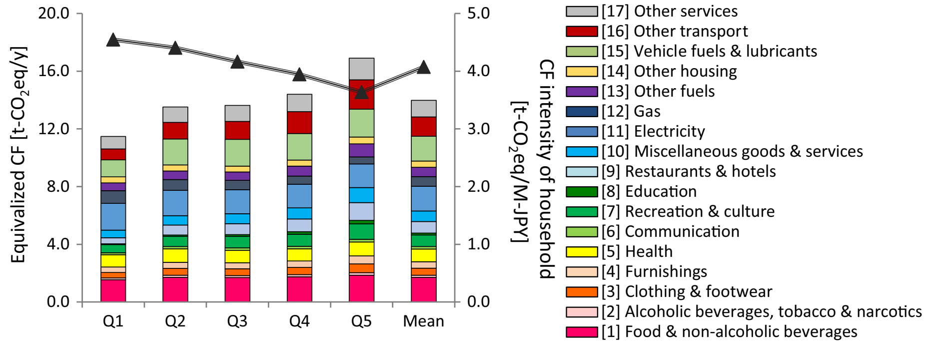

**Fig. 2** Equivalized carbon footprint (CF) (t-$CO_2$eq/y) for each household income quintile in 2005. *Triangles* denote the carbon footprint per unit expenditure (t-$CO_2$eq/M-JPY) for each household income quintile (corresponding to the *right vertical* axis)

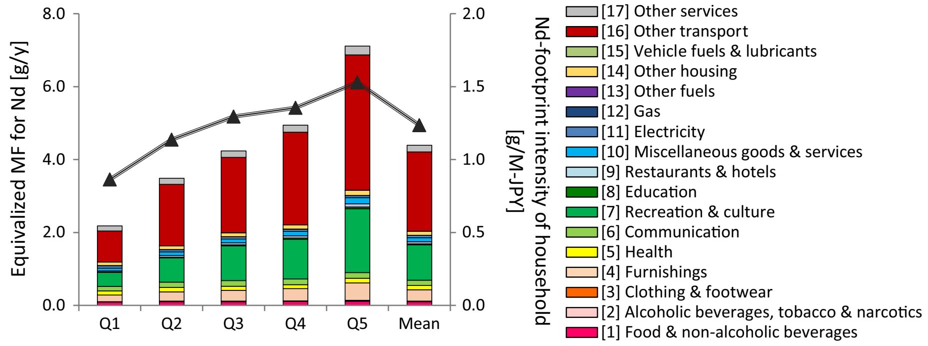

**Fig. 3** Equivalized material footprint (MF) for neodymium (t/y) for each household income quintile in 2005. *Triangles* denote the material footprint per unit expenditure (t/M-JPY) for each household income quintile (corresponding to the *right vertical* axis)

is approximately 1.8 times. When the breakdown is examined, for "other housing," which represents housing expenditures such as house rent and water bills but excludes "electricity" and "gas" usages, then the difference between Q1 (0.54M-JPY) and Q5

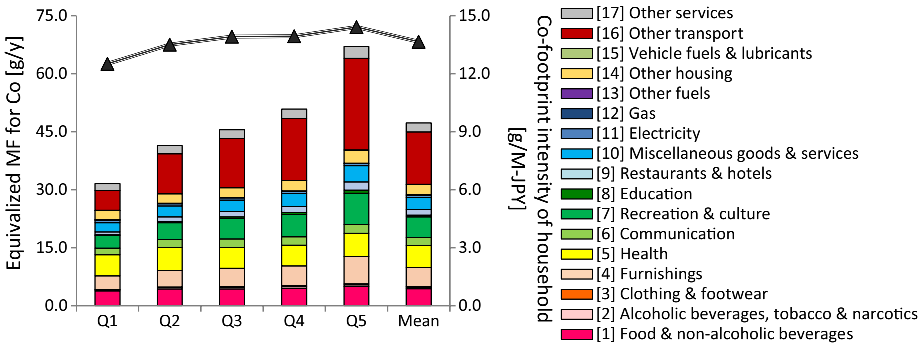

**Fig. 4** Equivalized material footprint (MF) for cobalt (t/y) for each household income quintile in 2005. *Triangles* denote the material footprint per unit expenditure (t/M-JPY) for each household income quintile (corresponding to the *right vertical* axis)

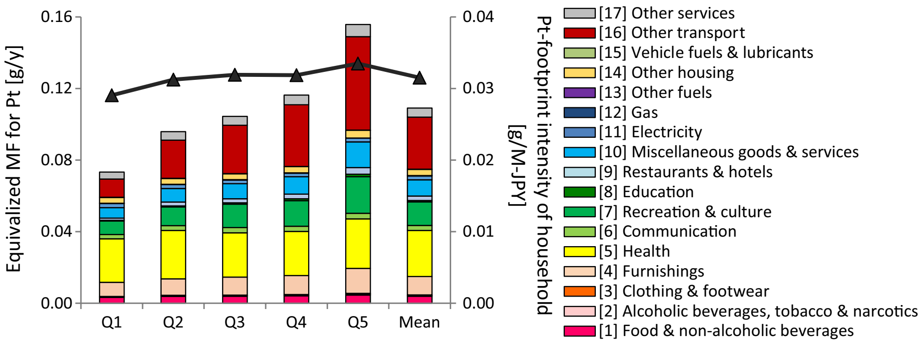

**Fig. 5** Equivalized material footprint (MF) for platinum (t/y) for each household income quintiles in 2005. *Triangles* denote the material footprint per unit expenditure (t/M-JPY) for each household income quintile (corresponding to the *right vertical* axis)

(1.13M-JPY) is 0.59M-JPY, which is the highest. The classifications that show the second and third largest difference between Q1 and Q5 are 0.34M-JPY (Q1: 0.48M-JPY, Q5: 0.82M-JPY) for "other services" and 0.27M-JPY (Q1: 0.16M-JPY, Q5: 0.43M-JPY) for "other transport," which consists of transport cost excluding vehicle fuel (e.g., private vehicle expenses and public transportation), respectively. However, of the COICOP categories, expenses on categories such as "health" do not necessarily rise as household income increases. For "gas," the value for Q1 (0.030M-JPY) is greater than that for Q5 (0.017M-JPY). Although this may seem somewhat surprising, one might infer that households with higher household incomes are larger in size, so when this is converted to a per-capita amount in the equivalized household, Q5 uses "gas" more efficiently.

For the share of consumption expenditure, the percentage of the total expenditure in categories related to food supply ("food and non-alcoholic beverages" and "alcoholic beverages, tobacco and narcotics") decreases from 13–9.0 % as household income increases. The share for expenditure in categories related to household energy ("electricity," "gas," and "other fuels") decreases from 4.2 to 2.0 % as income increases. The share for "restaurants and hotels," which reflects an increase in dining out, increases from 5.0 to 8.0 % alongside a reduction in the share of "food and non-alcoholic beverages" and "alcoholic beverages, tobacco and narcotics." The share of expenditure for "education" and "other transport," both of which show a significant difference between quintiles, increases from 1.5 to 3.4 % and from 6.5 to 9.2 % with increase in income, respectively.

### 3.2 Equivalized carbon footprint by household income quintile

The equivalized carbon footprints (t-$CO_2$eq/y) of the 17 categories and the carbon footprints per unit expenditure by income quintile are shown in Fig. 2. The carbon footprint increases as household income increases. The difference between the minimum quintile, Q1 (12 t-$CO_2$eq/y), and the maximum quintile, Q5 (17 t-$CO_2$eq/y), is about 1.4 times, and the average carbon footprint is 14 t-$CO_2$eq/y. Interestingly, despite the difference in expenditure between Q2 and Q3 being 0.20 M-JPY, the carbon footprints for these quintiles are nearly identical, and the carbon footprint only increases again from Q4 upwards. This trend differs from the relationship between household income and consumption expenditure where a steady increase is observed: the reason for this difference can be explained by analyzing the carbon footprints in each category. Detailed analysis reveals that the carbon footprints induced by "electricity," "vehicle fuels and lubricants," and "food and non-alcoholic beverages" are marked, and that the mean value for each category was 1.7 t-$CO_2$eq. Similarly, marked differences in carbon footprints between Q1 and Q5 are observed in "other transport," "restaurant and hotels," and "vehicle fuels and lubricants," which represent 1.2 t-$CO_2$eq/y, 0.83 t-$CO_2$eq/y, 0.76 t-$CO_2$eq/y, respectively. Although larger carbon footprints in these categories are induced in Q3 than in Q2, more "electricity" and "gas," which are highly carbon intensive categories, are consumed by Q2 than by Q3. This higher consumption of "electricity" and "gas" is the reason why the carbon footprints of these quintiles are very similar despite the total expenditure of Q3 being larger than that of Q2.

For the equivalized carbon footprint of each household, the share of both "food and non-alcoholic beverages" and "vehicle fuels and lubricants" is greater than 10 %. The proportion of the carbon footprint occupied by "restaurants and hotels" and "other transport" increases with annual household income. In Q5, the combined total of these two categories is as much as 19 %.

The carbon footprints per unit household expenditure (carbon footprint intensity of household) for Q1 to Q5 reveal that Q1, which was 4.6 t/M-JPY, is the most GHG-intensive quintile, while that of Q5 decreased to 3.6 t/M-JPY. This is because the share of "electricity" and "gas" for the lower-income households is larger than that for the higher-income households, for the reasons described in the comparisons of Q2 and Q3 above.

### 3.3 Equivalized material footprints by household income quintile

#### *3.3.1 Neodymium*

Figure 3 shows the equivalized material footprint for neodymium (g/y) in the 17 categories and the material footprint per unit expenditure for each household income quintile. As in the case of carbon footprints, the equivalized neodymium footprint increases as the household income rises. For example, the material footprints for Q1 and Q5 are 2.2 and 7.1 g/y, respectively, and the difference between the two quintiles is approximately 3.3 times; the average material footprint for neodymium is 4.4 g/y. When the material footprint is broken down by category, the contribution of "other transport" is considerable. This category includes usage of private cars, public buses, and taxis that have neodymium in their motors and audio systems. The material footprint for this category in Q5 is 3.7 g/y, which alone exceeds the combined material footprint for Q1 and Q2 and suggests that attention should be focused on expenditure on "other transport" in the high-income class.

In terms of the proportion of each category in the material footprint for neodymium, the sum of "other transport" and "recreation and culture" exceeded 50 % in all households, while the average share of each category is 48 and 21 %, respectively. In the latter category, a large contributor is high-tech electronic equipments, such as hard drives in personal computers. This trend toward an increase in the size of the material footprint becomes more apparent as the household income increases; for example, the sum of the shares of "other transport" and "recreation and culture" in Q5 accounts for 77 % of the whole.

In contrast to the carbon footprint intensity for households, a trend toward an increase in the material footprint for neodymium per unit household expenditure (Nd-footprint intensity of household) is observed as household income increases. This is because, compared to lower-income households, higher-income households can afford to purchase non-essential items, such as personal computers. The Nd-footprint intensity of household in Q5 reaches 1.5 g/M-JPY, which is 1.8 times the expenditure of 0.86 g/M-JPY in Q1.

### *3.3.2 Cobalt*

The total equivalized material footprint for cobalt increases by about 2.1 times from 32 g/y (Q1) to 67 g/y (Q5) as household income increases (Fig. 4). The average material footprint for cobalt is 47 g/y. When the material footprint is broken down by category, the contribution of "other transport" from Q2 to Q5 to the whole is the greatest. For Q1 only, "health" exceeds "other transport" by 0.33 g/y, and has the greatest contribution of 5.5 g/y. These categories appear to be related to heat resisting materials. "Food and non-alcoholic beverages," which could be associated with use of industrial inorganic chemicals, is the third largest category in Q1 (3.8 g/y) and Q2 (4.3 g/y). The difference in the cobalt material footprint between Q1 and Q5 is most marked in "other transport," and accounts for 5.1 and 24 g/y in both quintiles, respectively.

Regarding the proportion of each category in the material footprint for cobalt, a marked increase is observed in the share of "other transport," with the difference in the share of this category between Q1 (16 %) and Q5 (35 %) being nearly 20 %. The share in the three categories of "other transport," "furnishings," and "recreation and culture," exceeds 10 % in all households.

The Co-footprint intensity of household in Q5 reaches 14 g/M-JPY (maximum), which is similar to the 13 g/M-JPY (minimum) in Q1.

### *3.3.3 Platinum*

As household income increases, the total equivalized material footprint for platinum increases by approximately 2.1 times, from 0.073 g/y (Q1) to 0.16 g/y (Q5) (Fig. 5). The average material footprint for platinum is 0.11 g/y. The material footprint induced by "health" reaches maxima of 0.024 g/y (Q1) and 0.027 g/y (Q2). After Q3, the maximum material footprints induced by “other transport” in Q3–Q5 are 0.027 g/y, 0.035 g/y, and 0.052 g/y, respectively, implying that platinum is essential for both medicinal drugs and automobile catalysts. The maximum disparity between households is observed in “other transport,” which varies more than 5 times between Q1 (0.010 g/y) and Q5 (0.052 g/y).

Regarding the proportion of each category in the material footprint of platinum, the share of “other transport” rises with household income, increasing from 14 % (Q1) to 34 % (Q5). Conversely, the share of “health” decreases markedly from Q1 (33 %) to Q5 (18 %).

The Pt-footprint intensity of household changes only slightly, from 0.029 g/M-JPY (Q1) to 0.033 g/M-JPY (Q5), showing that this is similar among households, especially in the middle range (Q2–Q4).

## 4 Discussion

### 4.1 Common features of commodities contributing to each footprint

In order to elucidate the common characteristics of commodities consumed by households in terms of footprint generation, we compared footprints at the 409 commodity level. Hereafter, the names of the 409 commodities are written in *italics*.

The material footprints for three metals induced by *passenger motor cars* and *repair of motor vehicles* attributed to “other transport” were considerable, but *air transport* and *railway transport* (*passenger*) in the same category accounted for the majority of the carbon footprint. As described in the Results section, it is considered that the size of material footprints for neodymium and platinum are related to their utilization in car motors and audio systems, and automotive catalysts, respectively. In the case of cobalt, the size of the material footprint could be related to the use of heat-resistant materials for engine parts. The rechargeable batteries for hybrid vehicles and the metallic soap-based grease for wheels are also associated with cobalt usage.

Of the material footprints for cobalt that were induced by commodities related to “food and non-alcoholic beverages,” the contributions of *confectionery* and *soft drinks* were the highest, as both products are manufactured using equipment in which heat-resistant materials are used extensively. In the case of carbon footprints, *slaughtering and meat processing* and *frozen fish and shellfish* were large, presumably due to the energy that is required for farming processes and transportation. The material footprints for cobalt and platinum, as well as the carbon footprint induced by *medical services* in “health” were all noteworthy. Cobalt is used as a radioactive isotope in X-ray irradiation devices and as an alloy for implants, and platinum is used in pacemakers and syringes, and also as a catalyst in drug syntheses. Compared to the utilization of these metals in automobiles and household electric appliances, these applications are currently not considered to be very important in terms of resource recovery by recycling. Since the demand for medical care will likely increase as the domestic population ages and the number of children diminish (Shigetomi et al. 2014), any technical improvements and increases in “green” consumer behavior are considered to be important in reducing these footprints.

To analyze the degree of similarity among footprint patterns, we used Spearman’s rank correlation coefficients (Black et al. 2009) to compare footprints in terms of the rank of commodities arranged in descending order of each footprint value. The obtained correlations between carbon and material footprints were 0.34 (neodymium), 0.63 (cobalt), and 0.10 (platinum), indicating that the degree of similarity between the carbon and the cobalt footprints was highest. The rank correlation coefficient between material footprints was calculated to be 0.52 for neodymium and cobalt, 0.10 for neodymium and platinum, and 0.13 for cobalt and platinum. Since the degree of similarity among the material footprints of metals was not marked, relative differences in the demand for these target metals is considered important. Importantly, a reduction in the size of a material footprint depends on the type of footprint, which in turn differs depending on the commodity being utilized. Thus, by saving money through decreasing the consumption of gasoline, which has a high carbon footprint intensity, and then using those savings to buy a personal computer, which has a lower carbon intensity, the total carbon footprint is reduced. However, in such a situation, the size of the material footprint for neodymium will increase due to the higher Nd-footprint intensity for personal computers (the so-called rebound effect: e.g., Hertwich 2005).

### 4.2 Comparison with the UK case on carbon footprint

This section highlights the features of equivalized expenditures and carbon footprints and compares them to a study conducted in the UK (Chitnis et al. 2014). The UK study was conducted to clarify the relationship between household carbon footprint and income level with a global system boundary, and employed the same categorization for commodities as this study. Briefly, the common features and differences between the two studies are as follows. The equivalized expenditure of each quintile increases with household income. In the Japanese case (this study), the difference in expenditure between Q1 and Q5 was 1.8 times (2.53 and 4.65 M-JPY), while in the UK it was 5.2 times (€$4.7 \times 10^3$ and €$24.6 \times 10^3$), indicating the existence of a marked disparity between high- and low-income households in that country. However, in both Japan and the UK, consumption expenditures on “other housing” and “education” both increase markedly with increasing in household income. In Japan, the share of expenditure on “health” decreases as household income increases, while the share of “clothing and footwear” remains almost unchanged among households; this differs from the UK case in which the shares for both categories increase with household income. Generally, however, the share of expenditures in both countries is very similar.

For the relationship between the equivalized carbon footprints by quintile and household income, marked differences were observed between Japan and the UK. In Japan, the difference in the carbon footprint between Q1 and Q5 was 1.5 times (12 t-$CO_2$eq and 17 t-$CO_2$eq; average for all quintiles: 14 t-$CO_2$eq), while the difference between Q1 and Q5 in the UK was about 4.5-fold (about 6 t-$CO_2$eq and about 27 t-$CO_2$eq). Interestingly, the average equivalized carbon footprint per quintile in the UK was also about 14 t-$CO_2$eq, which is similar to that estimated in this study. Indeed, even the contribution of categories to the carbon footprint for each household income group is similar between Japan and the UK. For example, in both countries, the contribution of “other transport” increases as the household income increases. Furthermore, the share of the carbon footprints associated with goods that are essential for life, such as energy, city water, and food increases as the annual household income decreases. As in Chitnis et al. (2014), this study considered “food and non-alcoholic beverages,” “alcoholic beverages, tobacco and narcotics," "communication," "electricity," "gas," "other fuels," and "other housing" to be goods that are essential for life. The share of these categories in Q1 and Q5 was 48 and 34 % in Japan, and 57 and 27 % in the UK, respectively. In both countries, the carbon footprint per unit of household expenditure increases as household income decreases. The difference in the carbon footprint intensity for Q1 and Q5 is 25 % in Japan and 16 % in the UK.

Unlike carbon footprints, no previous studies have been conducted on the material footprints of the target metals caused by household consumption. Consequently, direct comparison with overseas data is not possible. However, based on similarities in the trend of equivalized expenditures and carbon footprints in the UK and Japan, it seems likely that the material footprints for neodymium, cobalt, and platinum instigated by household consumption are similar among developed countries. It is hoped that a similar analysis will be conducted to verify this possibility in foreign countries.

### 4.3 Policy implications of simultaneous carbon and material footprint analyses

The results reported herein show that carbon and material footprints both increase as household income increases. However, analysis of the relationship between household income and the size of a household's footprint per unit of household expenditure revealed that carbon and material footprints have contrasting characteristics. Thus, as household income increases, lifestyles likely shift to less GHG-intensive consumption, but more intensive on the use of metal resources. As described in Sect. 4.2, the former trend is seen in both Japanese and the UK households, even though the difference in the carbon footprint intensity of household between Q1 and Q5 in this study was larger than that in the UK. This difference in the trend suggests that if a carbon tax policy is implemented in Japan, then the tax burden on low-income groups will be higher than that on higher-income groups, and the extent of this burden will be higher than it is in the UK.

The fact that an increase in income leads to a decrease in carbon footprint intensity of household and an increase in their material footprint intensity is primarily attributable to gas and electricity having a relatively large carbon footprint intensity. Gas consumption does not increase with household income, but increased income is associated with an increase in the consumption of commodities related to amusement and transportation (e.g., dining out and traveling). In particular, payments for cars, especially for a second, or subsequent cars—the average number of cars owned by households is 0.51 in Q1 and 1.8 in Q5 (NSFIE, 2004)—and for durable products for amusement, such as personal computers, can strongly affect the material footprints for the critical metals examined in this study. A salient benefit of comparing footprints at the household level and how these footprints are affected by household income is that it is possible to consider how increases in consumption expenditures affect the footprints.

Within this context, factors affecting both material footprints and carbon footprints should be carefully considered when developing policies for mitigating global warming. For example, in Japan, preferential treatment was given to the replacement of old vehicles with fuel-efficient vehicles in an attempt to reduce carbon footprints (Kagawa et al. 2013). If subsidies or tax incentives are implemented for vehicles powered by fuel cells, then an increase in material footprints might be accelerated since it seems that an increase in income spurs purchases of cars and other commodities (rebound effect). In addition, national economic policies may also adversely affect households. For example, although the government of Japan announced that an increase in the average national income level is an economic goal, such an increase could result in material footprints increasing faster than carbon footprints. An increase in income would allow Q1 to adopt the lifestyle of Q5, resulting in the carbon footprint per-capita increasing 1.4 times, while the material footprints for neodymium, cobalt, and platinum would increase as much as 3.3 times, 2.1 times, and 2.1 times, respectively. This relationship between the carbon and material footprints is likely to apply to developing countries as well, where income levels are expected to increase markedly in the future.

It is considered that the methods described in this study for understanding the effects of reduction in GHG emissions and increased economic activity on both carbon and material footprints can also be applied to predicting the trade-offs between global warming, resource consumption, and economic growth.

## 5 Conclusions

We examined the structure of trade-offs between carbon and material footprints for neodymium, cobalt, and platinum, caused by Japanese household consumption. The footprints were calculated according to household income quintile using the GLIO model. In addition, the square root scaling method was employed to compare footprints among households in order to clarify differences in household size and their footprint characteristics.

The findings of this study confirmed that reduction of carbon and material footprints in households requires that the consumption of commodities be selective and carefully considered. Visualization of carbon footprints using methods such as carbon footprint labeling helps communicate to consumers how reductions in household consumption can be effective for reducing GHG emissions. Using such visualization methods to communicate material footprints will help make consumers aware of the differences between carbon and material footprints, and how households can contribute toward limiting resource consumption and improving resource efficiency.

The results also showed that private motor cars, household electric appliances, and high-tech products all contribute significantly to the material footprints for neodymium, cobalt, and platinum, and that the material footprints induced by the utilization of these metals increases with household income. Therefore, if economic policy focuses on increasing the level of household income, then reducing material footprints by encouraging consumers to reuse products and extend product lifetimes is considered necessary. Conversely, for medical services that have relatively large cobalt and platinum footprints, achieving a reduction in utilization is nearly impossible given the high demand for these services. For this reason, focusing on technological improvements and seeking alternative materials are considered priorities, as is the extraction of these metals from obsolete medical equipment. Finally, educating people in the benefits of good health would not only decrease individual medical costs, but also effectively reduce the size of these footprints.

Thus, innovations in consumption and production that are directed at reducing the size of both carbon and material footprints would likely make a significant contribution toward the establishment of a low-carbon and resource-efficient society and ensure sustainable development in the future.

## Authors' contributions

YS, KN and ST proposed the methodology and provided policy implications. YS was in charge of data collection and conducted data analysis. KN and SK developed the MRIO model. All authors read and approved the final manuscript.

## Author details

[1] Graduate School of Energy Science, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto, Kyoto 606-8501, Japan. [2] Center for Material Cycles and Waste Management Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaragi 305-8506, Japan. [3] Research Fellow of Japan Society for the Promotion of Science, Tokyo, Japan. [4] Faculty of Economics, Kyushu University, 6-19-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan.

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## Competing interests

The authors declare that they have no competing interests.

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